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THE EFFECTS OF ROUGHNESS AT HIGH REYNOLDS NUMBERS
ON THE LIFT AND DRAG CHARACTERISTICS
OF THREE THICK AIRFOILS

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ADVANCE CONFIDENTIAL REPORT

THE EFFECTS OF ROUGHNESS AT HIGH REYNOLDS NUMBERS
ON THE LIFT AND DRAG CHARACTERISTICS
OF THREE THICK AIRFOILS

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SUMMARY

In connection with studies of airfoils applicable to large high-speed aircraft, the effects of roughness on three 22-percent-thick airfoils were investigated. The tests were made over a range of Reynolds number from about 6 to 26×10^6 for the airfoils smooth and with roughness strips applied to the surfaces. The results indicated that for the roughened models the scale effect was generally favorable.

INTRODUCTION

Previous tests in the NACA two-dimensional low-turbulence pressure tunnel of thick airfoils with roughened leading edges (reference 1) indicated that the lift and drag characteristics of the thicker wing sections, when accidentally roughened, would have an important bearing on the choice of sections for large high-speed airplanes. These tests were limited to Reynolds numbers much lower than the flight values for such airplanes by the use of 2-foot-chord wooden models.

The desirability of extending the tests to higher values of the Reynolds number was apparent, and an aircraft manufacturer submitted three 3-foot-chord models of heavy metal construction for this purpose. The three airfoil sections were: an NACA 63(420)-422 airfoil; an NACA 65(223)-422, $a = 1.0$ (approx.) airfoil, where "(approx.)" refers to a slight thickening near the trailing edge; and a 22-percent-thick Davis airfoil. These models were tested in the NACA two-dimensional low-turbulence pressure tunnel in order to obtain lift

and drag characteristics at Reynolds numbers up to approximately 26×10^6 with smooth surfaces, with roughness grains of various sizes on the leading edges, and in some cases with roughness strips at various chordwise positions.

TEST METHODS

All tests were conducted in the NACA two-dimensional low-turbulence pressure tunnel, which is characterized by an air stream of extremely low turbulence. The models extended from wall to wall of the rectangular test section. Lift measurements were obtained by a manometer arrangement that integrated the lift reaction of the models on the floor and ceiling of the tunnel, and drag measurements were made by the wake-survey method (reference 2). A correction of about 2 percent was applied to the data for normal tunnel-wall-constriction effects. Lift coefficients near maximum lift were further corrected for additional tunnel blocking that occurs when the model is partially stalled. These additional corrections, derived from static-pressure measurements made along the floor and ceiling of the tunnel, varied from 0 to about 10 percent. Tests were made at tunnel tank pressures from 30 pounds per square inch to 150 pounds per square inch and, at all times, the tunnel airspeed was low enough to avoid compressibility effects.

The airfoils submitted by the aircraft manufacturer had 36-inch chords, were of heavy metal construction, and were painted to give aerodynamically smooth surfaces. The two low-drag airfoils were tested first smooth, then with various sizes of roughness on the leading edge, and finally with 0.011-inch roughness grains at one or more chordwise positions. The Davis airfoil was tested smooth and with roughness grains of two sizes on the leading edge.

Tests were made of all three models, both smooth and rough, at Reynolds numbers of approximately 6, 10, 14, 20, and 26×10^6 .

The roughness sizes of 0.002, 0.004, and 0.011 inch represent the average size of the carborundum grains used. The roughness was applied to the leading edge

by coating a strip from 5.50 to 5.75 inches wide, symmetrically spaced about the chord line at the leading edge, with thinned shellac and sprinkling with carborundum grains until 5 to 10 percent of the area was covered with grains. The roughness strips at 20 percent and 30 percent of the airfoil chord (0.20c and 0.30c) were similarly applied but were 0.5 inch wide with the forward edge of the strip at the specified chordwise location.

RESULTS AND DISCUSSION

NACA 63(420)-422 Airfoil

The effects on the lift and drag characteristics of four sizes of roughness applied to the leading edge of the NACA 63(420)-422 airfoil section at a Reynolds number of 26×10^6 are shown in figure 1. The loss in maximum lift tended to be gradual with increasing roughness size, but the increase in drag coefficient in the low-drag range was not gradual. The application of shellac alone to the leading edge caused a large increase in drag coefficient in this range. The shellac, however, did not decrease the lift coefficient at which the drag increased sharply to extremely high values, whereas all other roughness sizes on the leading edge did.

The effects of the 0.011-inch-grain roughness at various chordwise positions are shown in figure 2. There was no large detrimental effect on maximum lift unless the roughness was on the leading edge. This result is attributed to the fact that at maximum lift the shape of the pressure distribution causes transition on the upper surface to occur close to the leading edge. The effect of roughness, therefore, in the thick turbulent boundary layer downstream of the pressure peak would be expected to be small in comparison with the effect of roughness in the relatively thin boundary layer at the leading edge. The drag coefficients at low and moderate lift coefficients increased as the roughness was moved toward the leading edge, as would be expected from the accompanying forward movement of transition. The roughness strips at 0.20c and 0.30c, however, did not appreciably affect the value of the lift coefficient at which the drag increased to extremely high values. At these

locations, the boundary layer cannot be laminar at such lift coefficients because of the shape of the pressure distributions.

The scale effect on the lift and drag characteristics of three sizes of roughness on the leading edge is shown in figures 3 to 5. These plots show, in general, a gradual decrease in drag and an increase in maximum lift with increasing Reynolds number - that is, the scale effect was considered favorable - for all three sizes of roughness.

NACA 65(223)-422 (Modified) Airfoil

Lift and drag characteristics of the NACA 65(223)-422 (modified) airfoil are shown in figure 6 for four model conditions; namely, 0.004-inch-grain roughness on the leading edge, 0.011-inch-grain roughness on the leading edge, 0.011-inch-grain roughness at 0.30c, and smooth at Reynolds numbers of 14 and 26×10^6 . The curves for the model in a smooth condition are presented to show that this section had a gradual increase in drag with increasing Reynolds number - that is, the scale effect was considered adverse - in the low-drag range. This result was probably caused by some slight surface irregularity which, because of the small slopes of the favorable pressure gradients of this section, make it unusually sensitive to any surface defects and unfairness. It is thought that lower drags than are shown for this section are possible, but NACA 65-series airfoils (reference 2) which are preferable to the one tested are now available.

The application of roughness to the leading edge of the NACA 65(223)-422 (modified) airfoil seriously decreased the maximum lift and caused a large decrease in the lift coefficient at which the drag increased rapidly. The greater part of the drag increment attributed to the roughness grains was caused by the smallest roughness size tested. The roughness strip at 0.30c did not affect the maximum lift coefficient to any great extent, because the flow over the top surface of the airfoil at this high positive angle of attack had become turbulent much nearer the leading edge.

The effects of 0.004-inch-grain and 0.011-inch-grain roughnesses applied to the leading edge at Reynolds numbers from 6 to 26×10^6 are shown in figures 7 and 8, respectively. The scale effect was

generally favorable, especially in the case of the drag coefficients, but became very small at Reynolds numbers of 20 to 26×10^6 . The increase with Reynolds number of the value of the lift coefficient at which the drag coefficient increased sharply was especially notable.

Davis Airfoil

Lift and drag data for the Davis airfoil in the smooth condition and with 0.002-inch-grain and 0.011-inch-grain roughnesses applied to the leading edge are presented in figure 9. A comparison of the lift and drag curves obtained for the smooth model with the curves obtained with roughness on the model shows that even the smaller (0.002-inch grain) roughness caused a loss in maximum lift coefficient of approximately 0.4, a slight decrease in lift-curve slope, and a large increase in drag throughout the range tested.

Results of tests with roughness grains of 0.002 and 0.011 inch on the leading edge at Reynolds numbers from 6 to 26×10^6 are presented in figures 10 and 11, respectively. Scale effect on the drag coefficients was favorable for both sizes of roughness but became small at Reynolds numbers of 20 and 26×10^6 . There was a small favorable scale effect on the maximum-lift values up to Reynolds numbers of 20×10^6 and small adverse scale effect for both sizes of roughness at Reynolds numbers from 20 to 26×10^6 .

COMPARISON OF AIRFOIL SECTIONS

The drag coefficients of the NACA 63(420)-422 airfoil section and the NACA 65(223)-422 (modified) airfoil section with roughness strips of 0.011-inch grain at 0.30c are compared in figure 12. In this condition the extent of the laminar boundary layer should be the same for both sections at lift coefficients corresponding to the low-drag range for the smooth airfoils. The drag coefficients were nearly the same for lift coefficients below about 1.2; the differences shown are not considered greater than

possible variations for tests with roughness. Figure 13 shows a similar comparison for the three airfoils tested with 0.011-inch-grain roughness on the leading edges. The NACA 63(420)-422 section was more resistant to separation when rough than the other two sections; that is, the lift coefficient at which the drag coefficients rise sharply to very high values was appreciably higher for this section than for the other sections tested. Numerous spanwise drag surveys were made of the three models with roughness on the leading edges. These surveys showed that the NACA 63(420)-422 airfoil had no localized separation up to moderately high lift coefficients, that the NACA 65(223)-422 (modified) airfoil showed marked local separation at much lower lift coefficients, and that the Davis airfoil showed local separation at lift coefficients above approximately 0.8.

The effects on the drag coefficient at a lift coefficient of 0.4 of various sizes of roughness on the leading edge for the three airfoils tested are shown in figure 14. All three airfoils had nearly the same drag coefficient when rough and the drag increased very little with increasing roughness size. A large increase occurred, however, from the smooth condition to the smallest size of roughness.

Both the NACA low-drag airfoils were affected by roughness less at the high Reynolds numbers than at the lower Reynolds numbers. This favorable scale effect with the models in a rough condition increased the lift coefficients at which the drag coefficients increased rapidly to extremely high values by nearly 0.4 for the NACA 65(223)-422 (modified) section and 0.2 for the NACA 63(420)-422 section. The Davis airfoil showed practically no favorable scale effect in this respect although the effect on drag coefficient at lower lift coefficients was favorable.

CONCLUSIONS

Tests of an NACA 63(420)-422 airfoil, an NACA 65(223)-422 (modified) airfoil, and a 22-percent-thick Davis airfoil, all with roughness strips on the surfaces, indicated the following conclusions:

1. In general, the airfoils with roughness strips showed favorable scale effects over the Reynolds number

range from 6 to 26×10^6 . This favorable scale effect was particularly effective on the NACA airfoils in increasing the lift coefficients at which the drag coefficients increased sharply to very high values.

2. At small and moderate lift coefficients, the drag coefficients for all the sections tested with leading edges rough were nearly the same for the same roughness condition and Reynolds number. With roughness strips at 30 percent of the chord, the drag characteristics of the two NACA airfoils tested were nearly the same except at the highest lift coefficient.

3. Increasing the size of the roughness grains applied to the leading edge progressively decreased the maximum lift coefficients for the sizes tested, but the greater part of the drag increment caused by the roughness occurred with the smallest roughness tested.

4. The order of merit of the three airfoils in permitting high lift coefficients to be obtained without excessively high drag coefficients with the leading edges rough is as follows: the NACA 63(420)-422 airfoil, the NACA 65(223)-422 (modified) airfoil, and the 22-percent-thick Davis airfoil.

5. The maximum lift coefficients of the NACA airfoils tested were not affected to any great extent by roughness strips at 20 or 30 percent of the chord back of the leading edge.

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2. Abbott, Ira H., von Doenhoff, Albert E., and Stivers, Louis S., Jr.: Summary of Airfoil Data. NACA ACR No. 15C05, 1945.

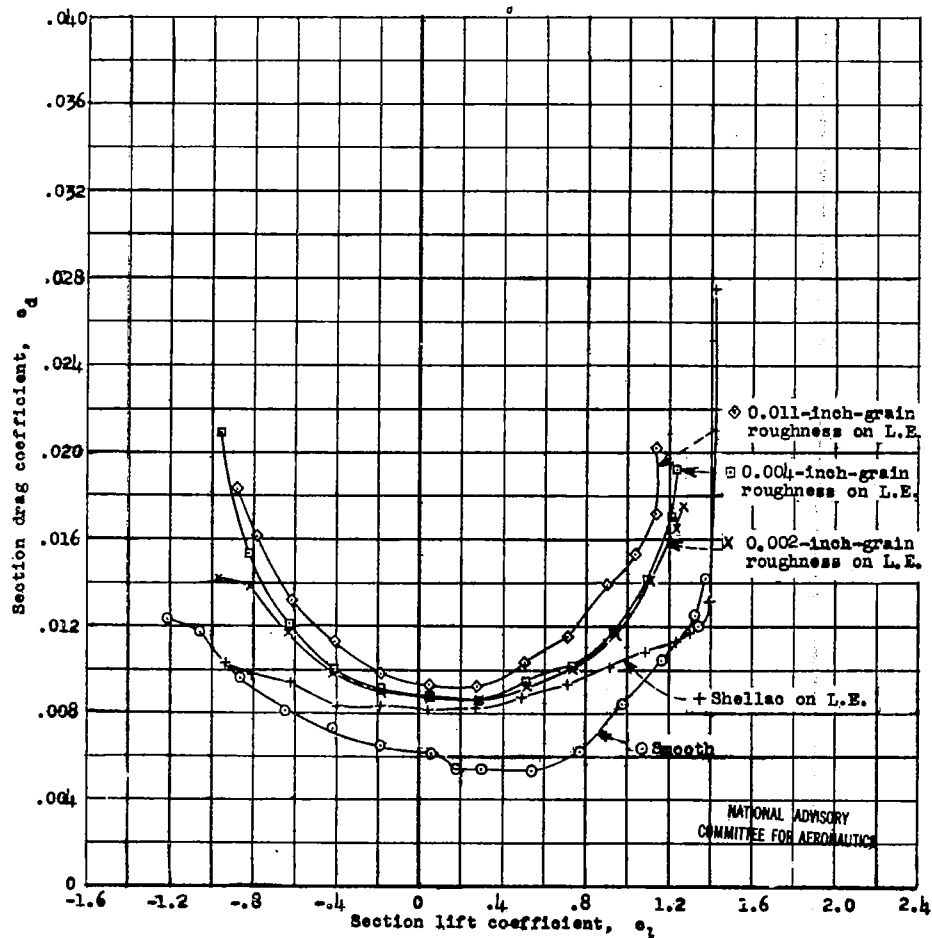
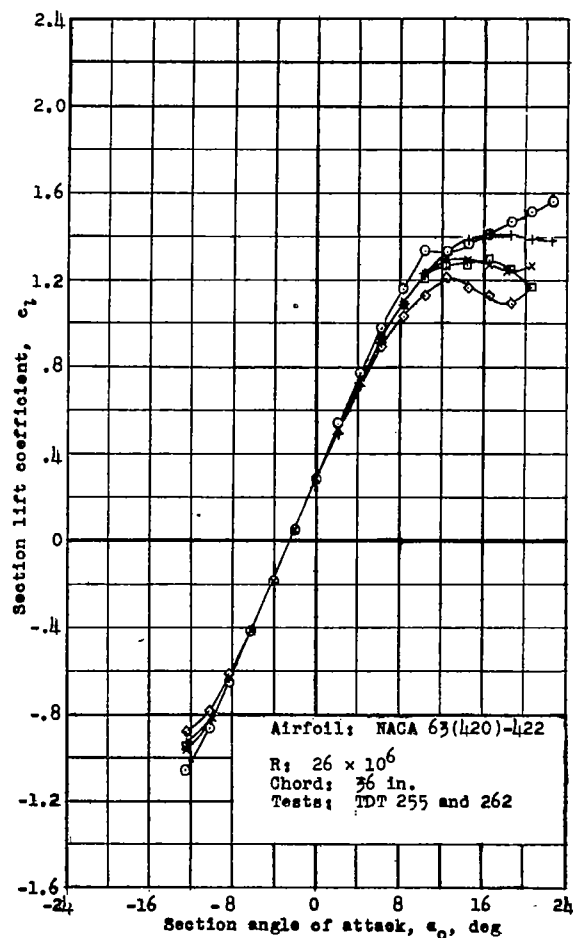


Figure 1.- Lift and drag characteristics of an NACA 63(420)-422 airfoil with various roughnesses applied to the leading edge.

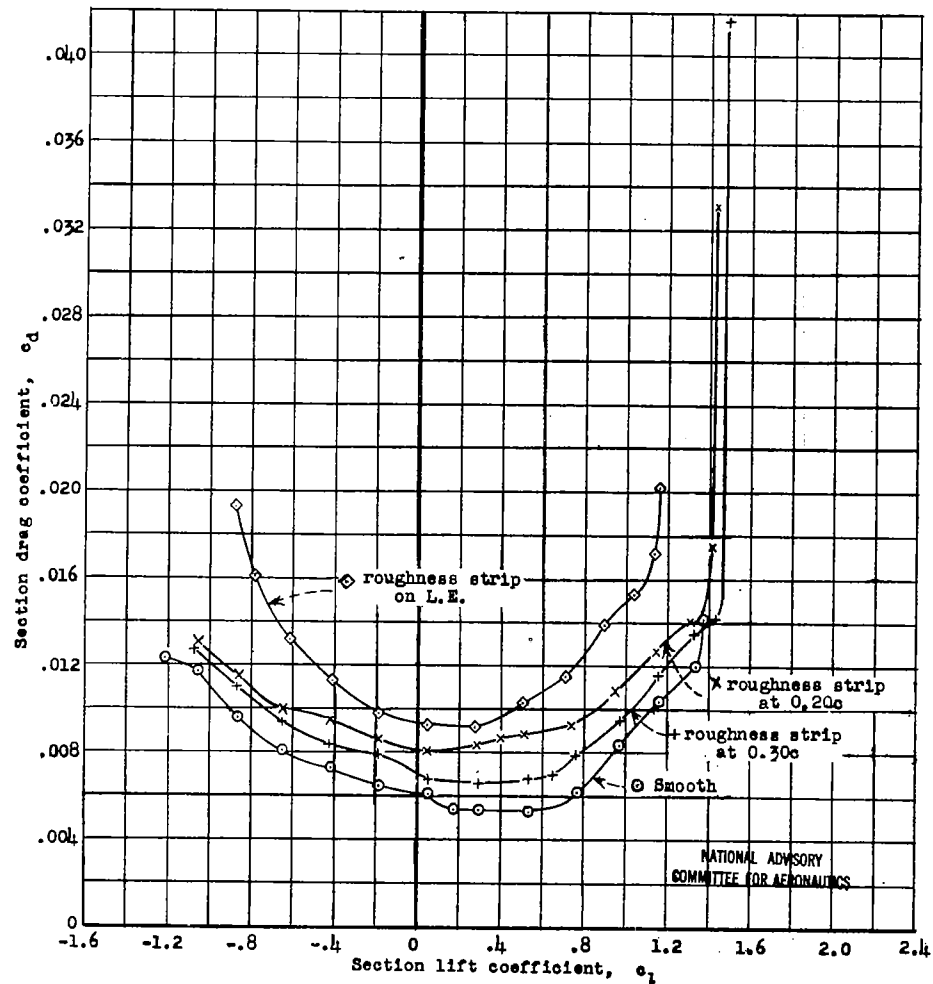
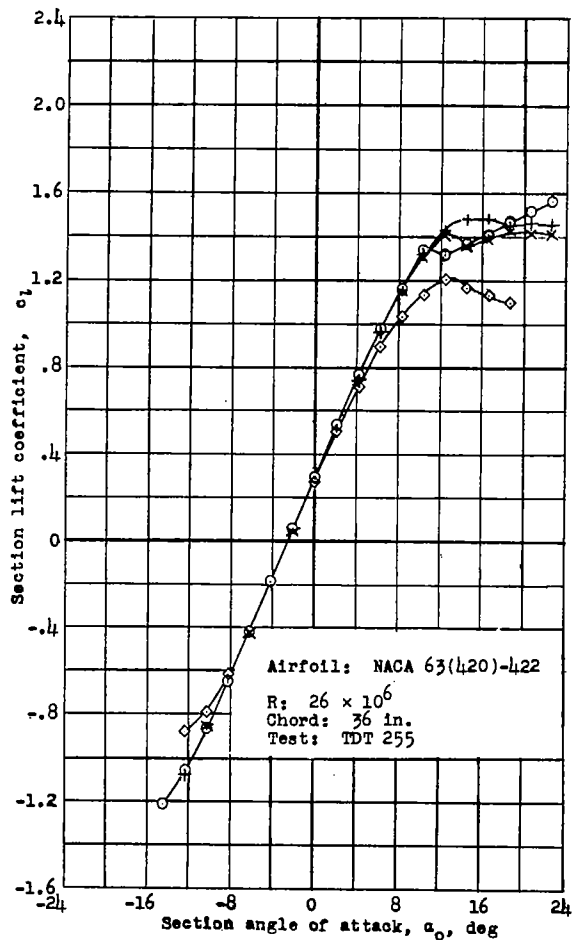


Figure 2.- Lift and drag characteristics of an NACA 63(420)-422 airfoil with 0.011-inch-grain roughness at various chordwise locations.

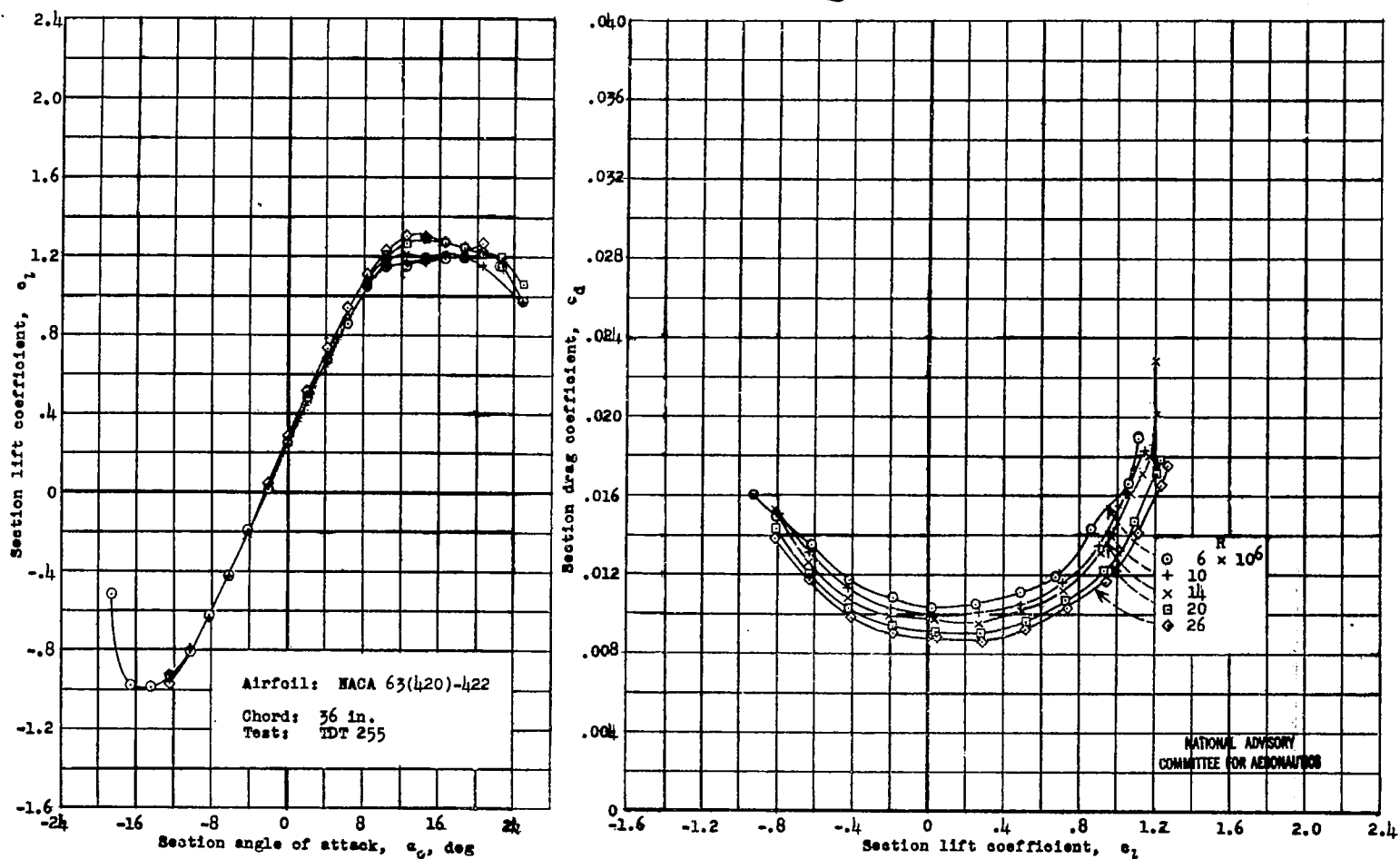


Figure 3.- Lift and drag characteristics of an NACA 63(420)-422 airfoil with 0.002-inch-grain roughness applied to the leading edge.

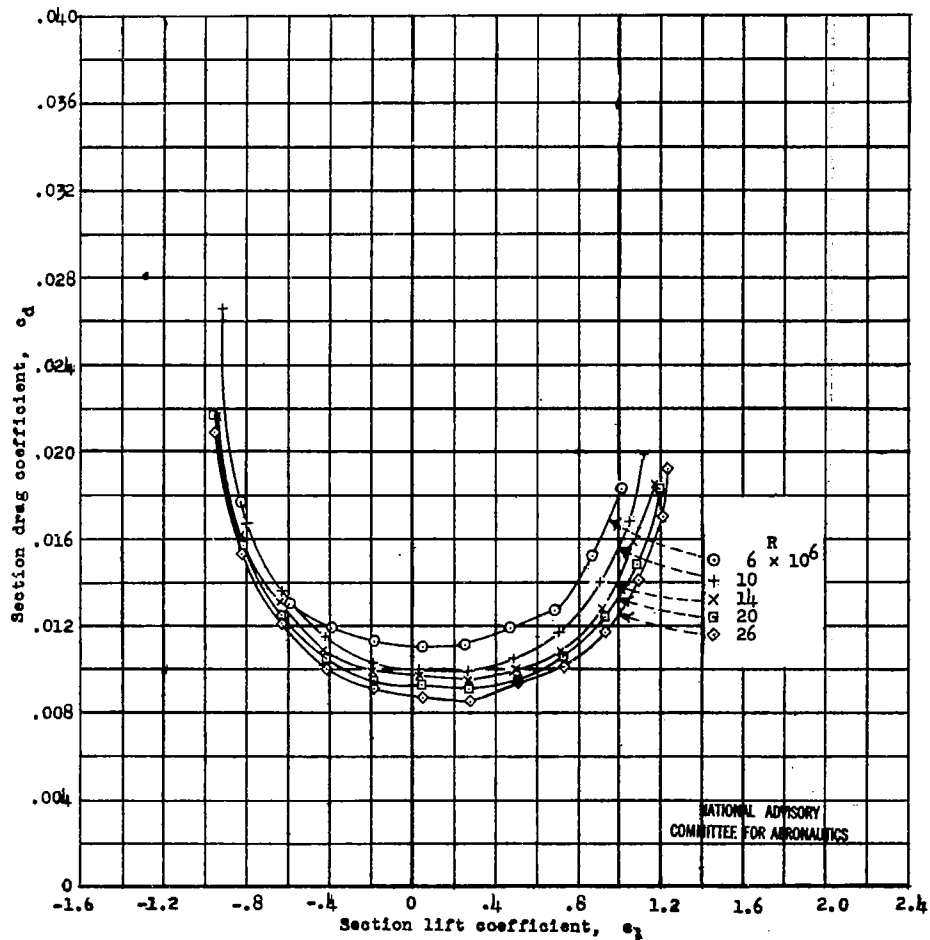
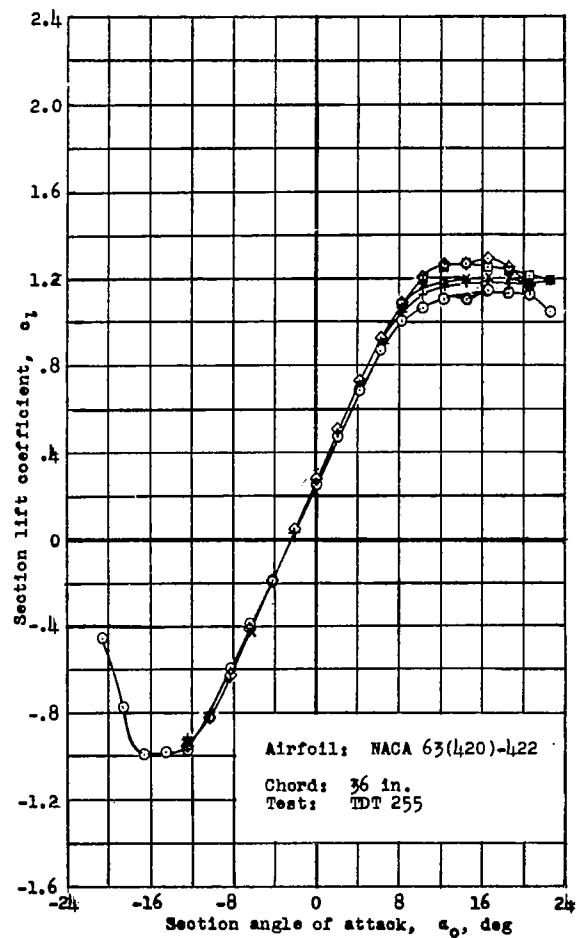


Figure 4.- Lift and drag characteristics of an NACA 63(420)-422 airfoil with 0.004-inch-grain roughness applied to the leading edge.

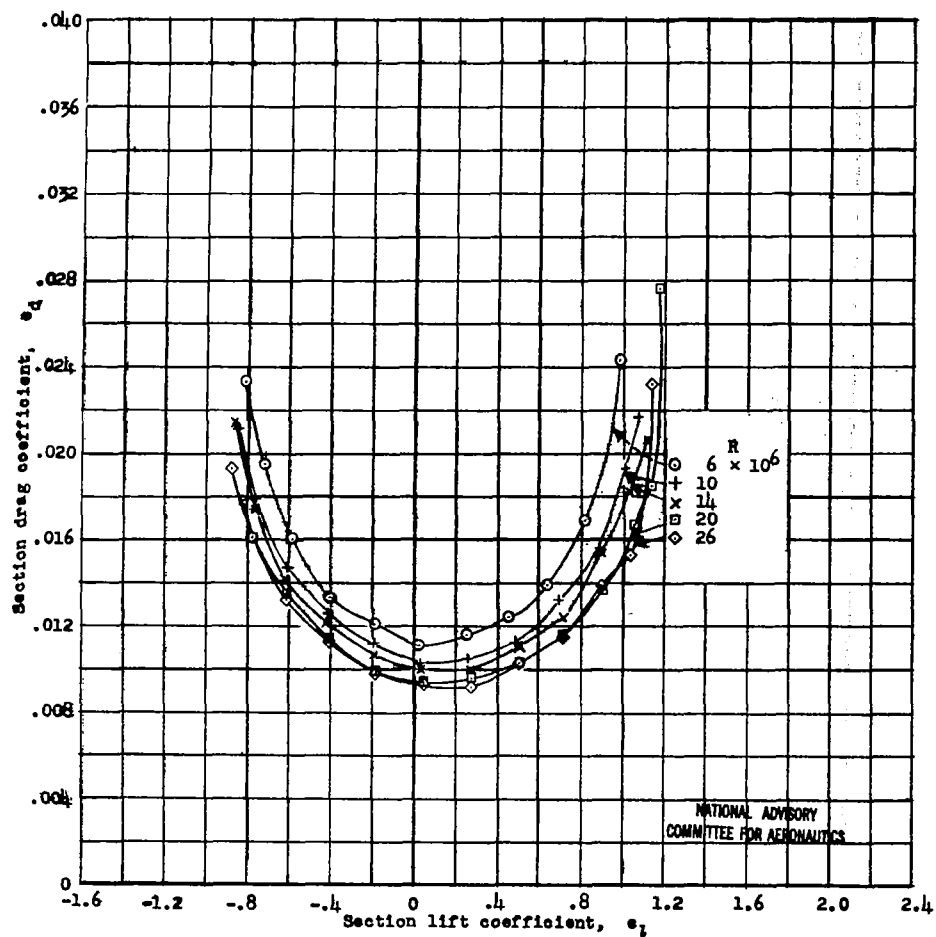
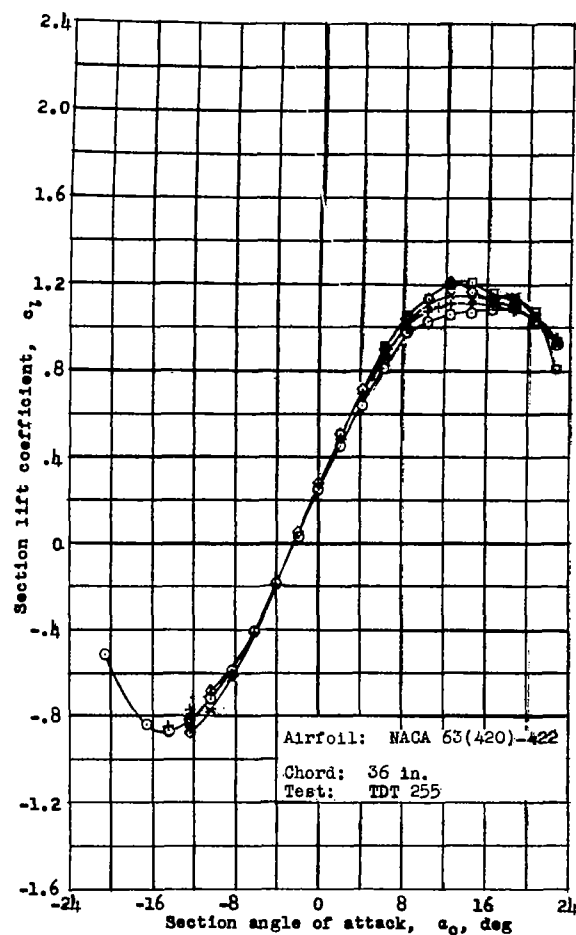


Figure 5.- Lift and drag characteristics of an NACA 63(420)-422 airfoil with 0.011-inch-grain roughness applied to the leading edge.

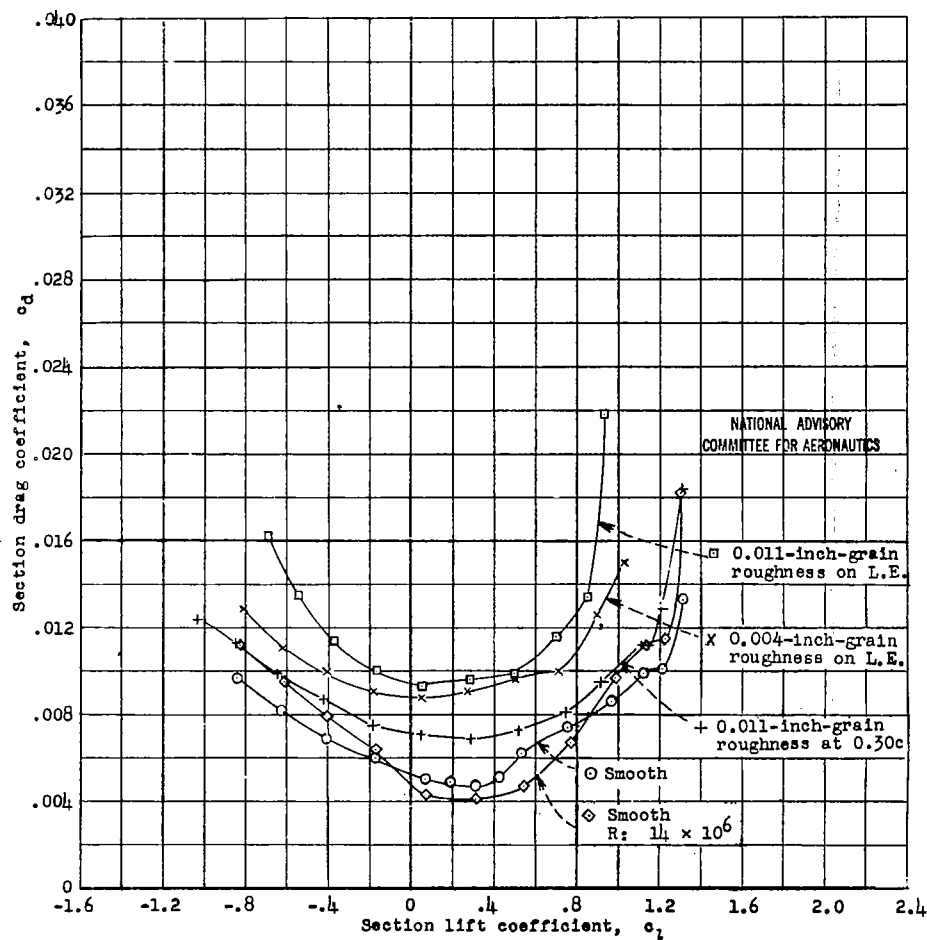
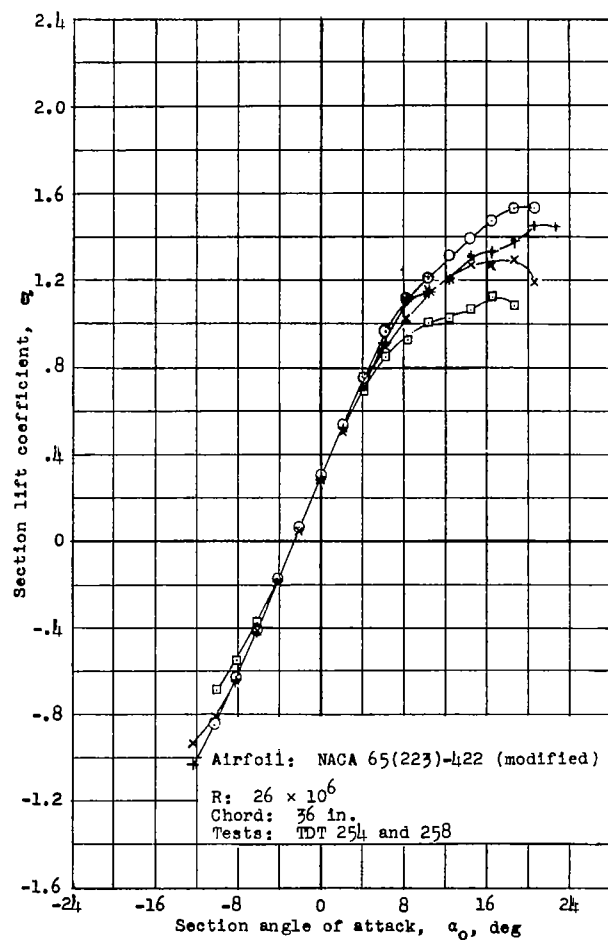


Figure 6.- Lift and drag characteristics of an NACA 65(223)-422 (modified) airfoil with various roughnesses.

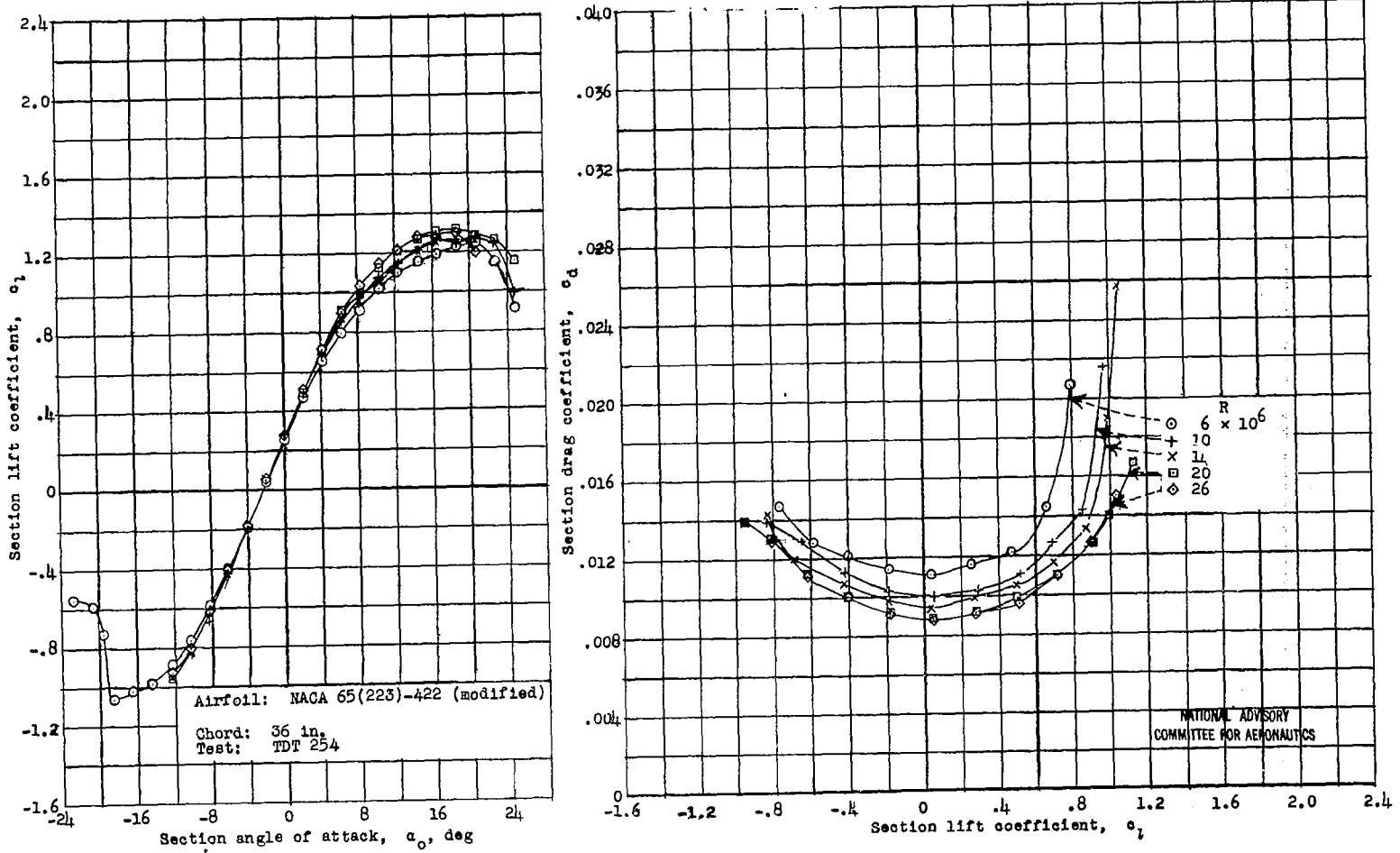


Figure 7.- Lift and drag characteristics of an NACA 65(223)-422 (modified) airfoil with 0.004-inch-grain roughness applied to the leading edge.

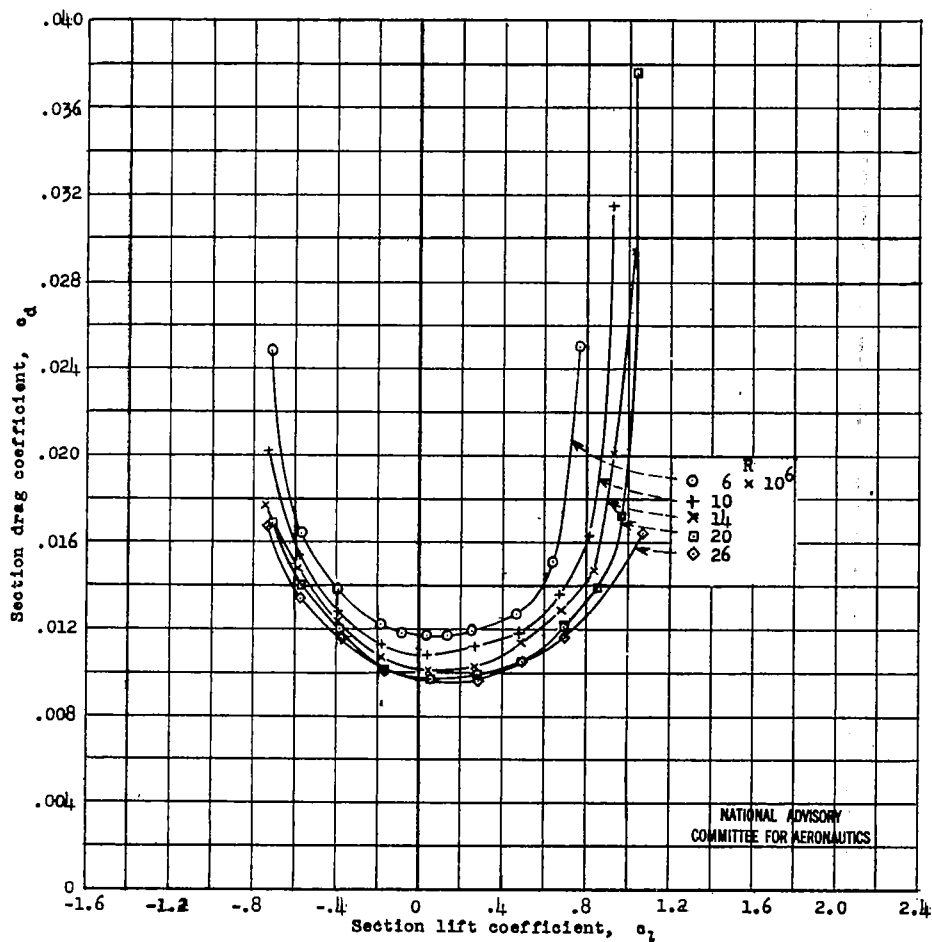
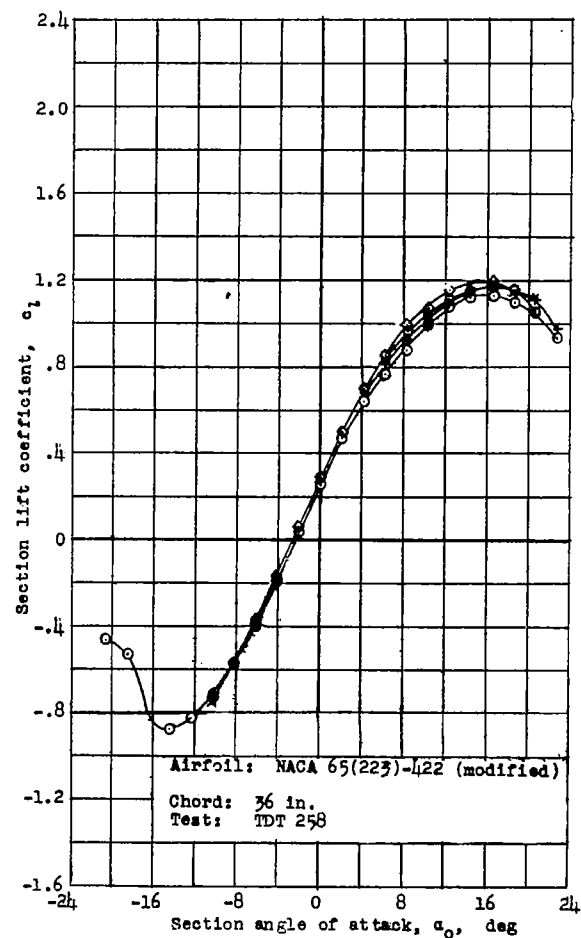


Figure 8.- Lift and drag characteristics of an NACA 65(223)-422 (modified) airfoil with 0.011-inch-grain roughness applied to the leading edge.

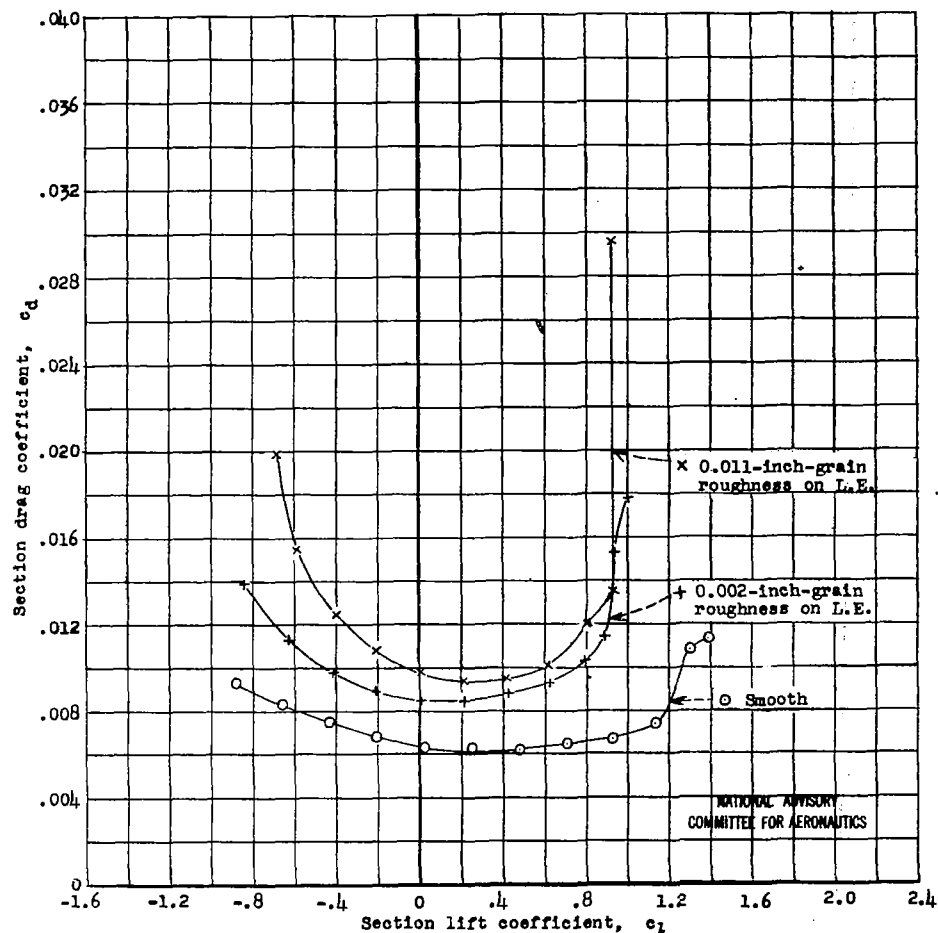
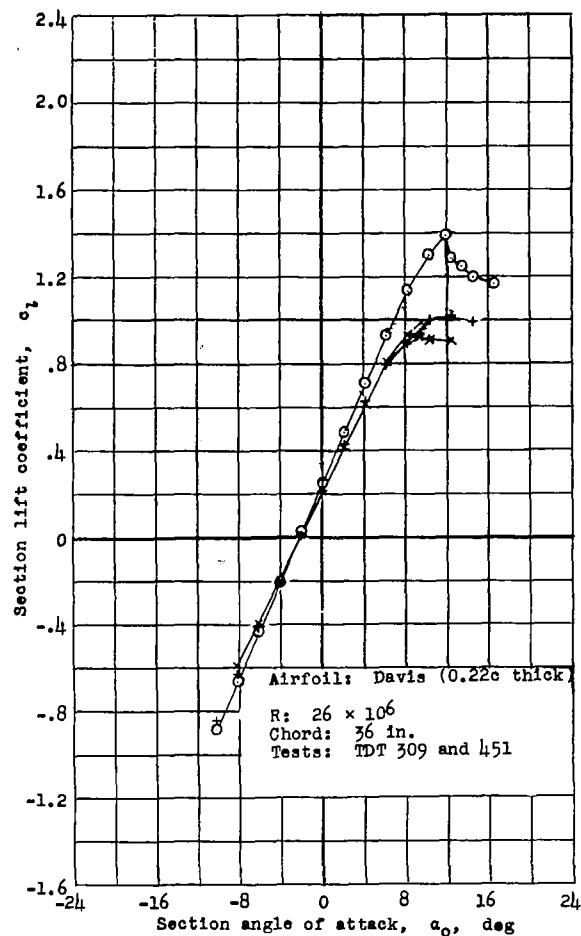


Figure 9.- Lift and drag characteristics of a 0.22c-thick Davis airfoil with two sizes of roughness grains applied to the leading edge.

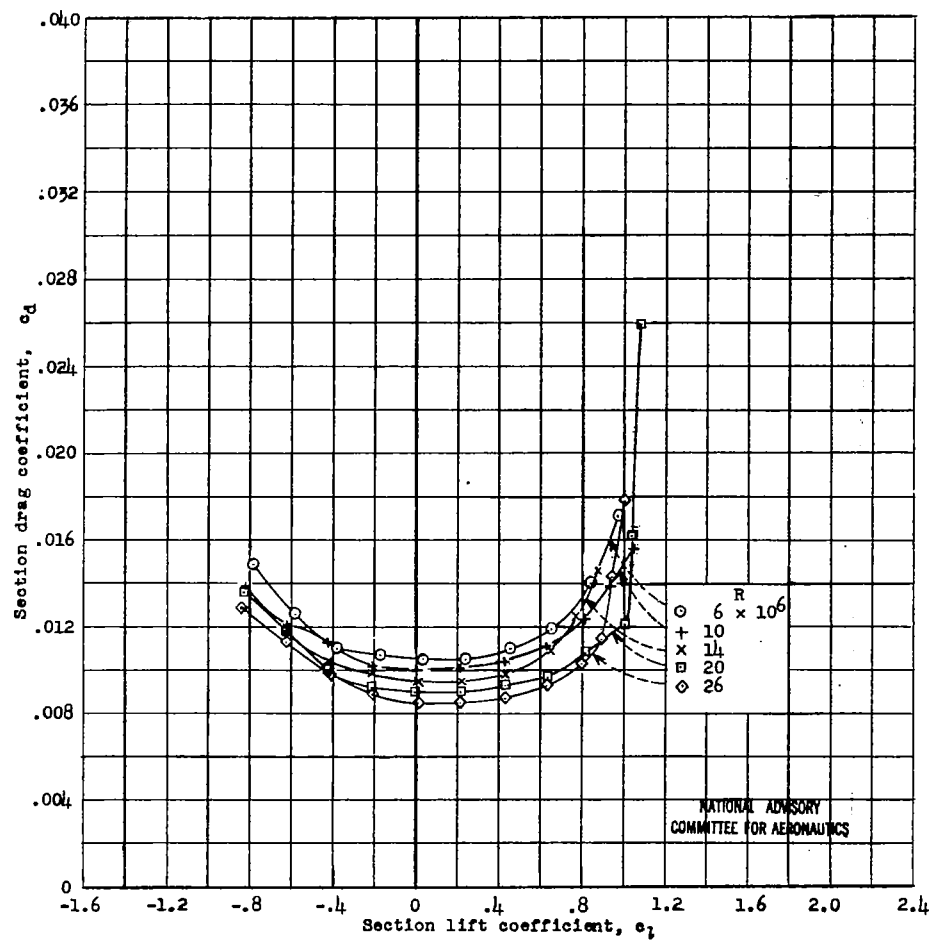
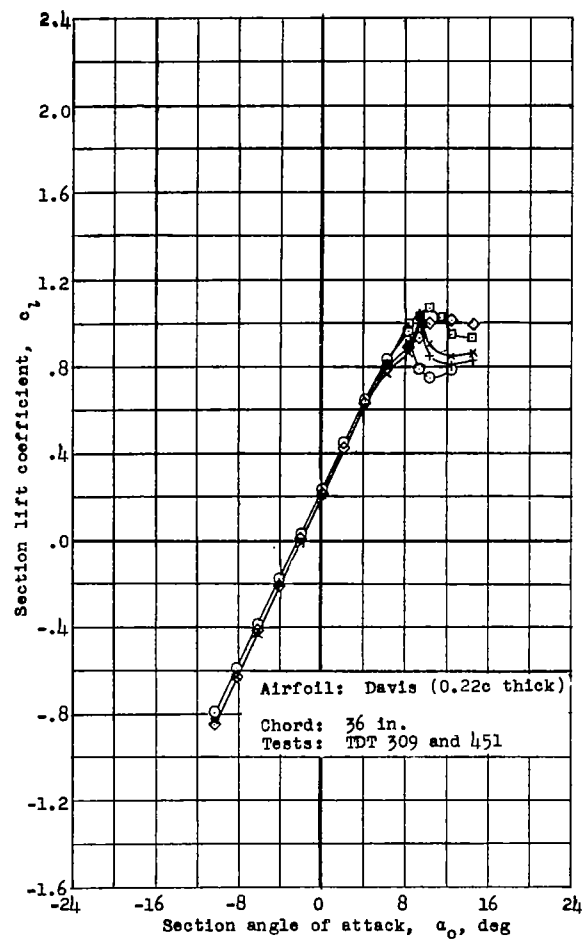


Figure 10.- Lift and drag characteristics of a 0.22c-thick Davis airfoil with 0.002-inch-grain roughness applied to the leading edge.

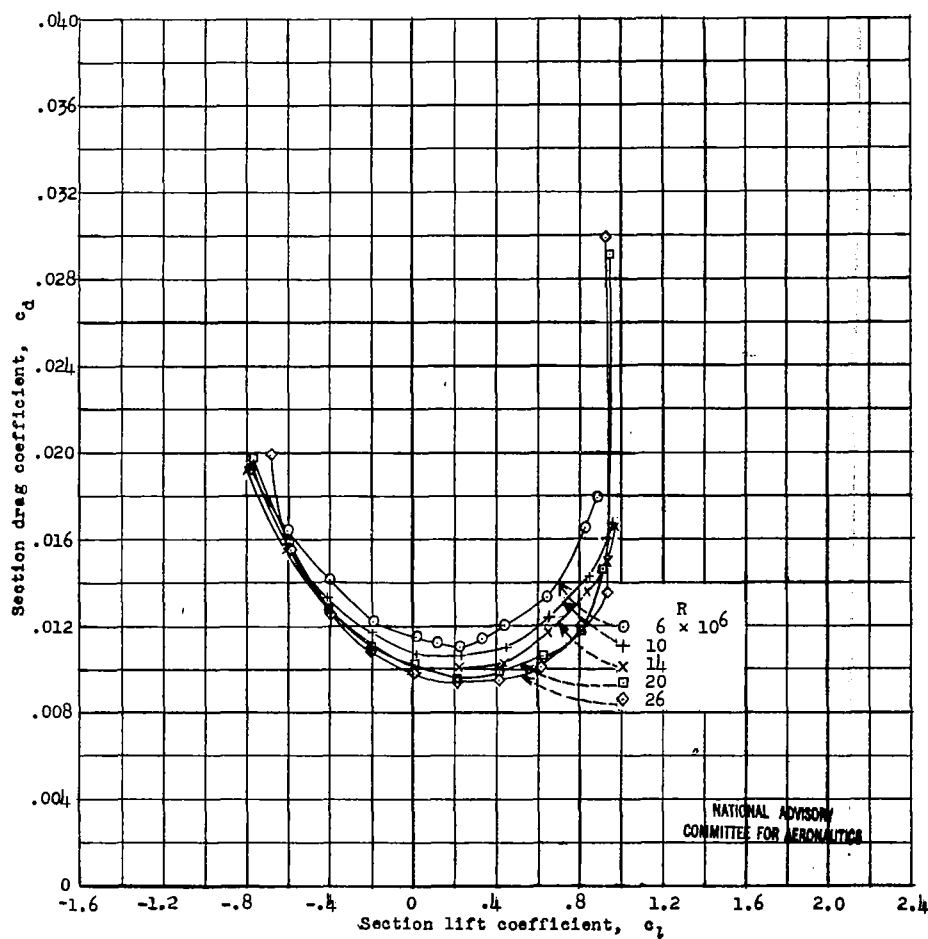
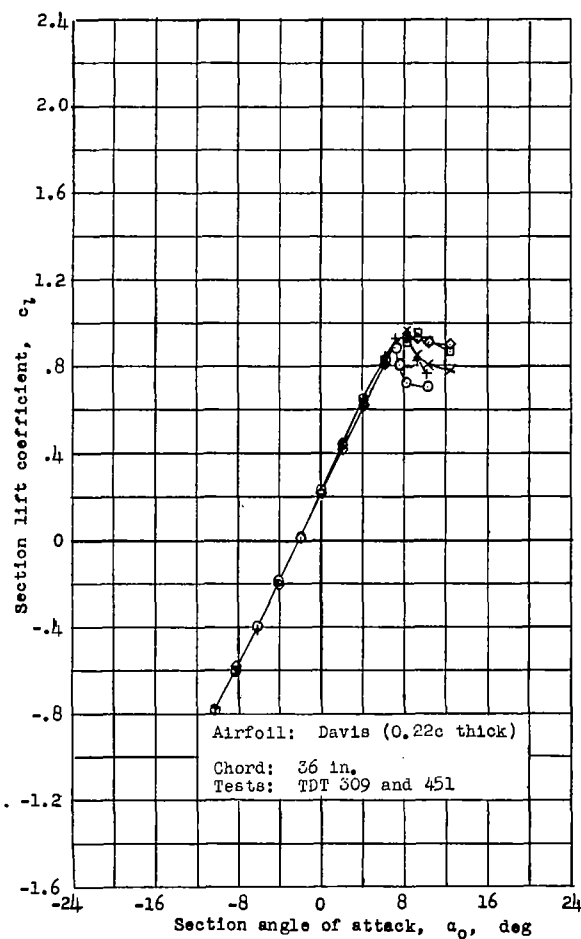


Figure 11.- Lift and drag characteristics of a 0.22c-thick Davis airfoil with 0.011-inch-grain roughness applied to the leading edge.

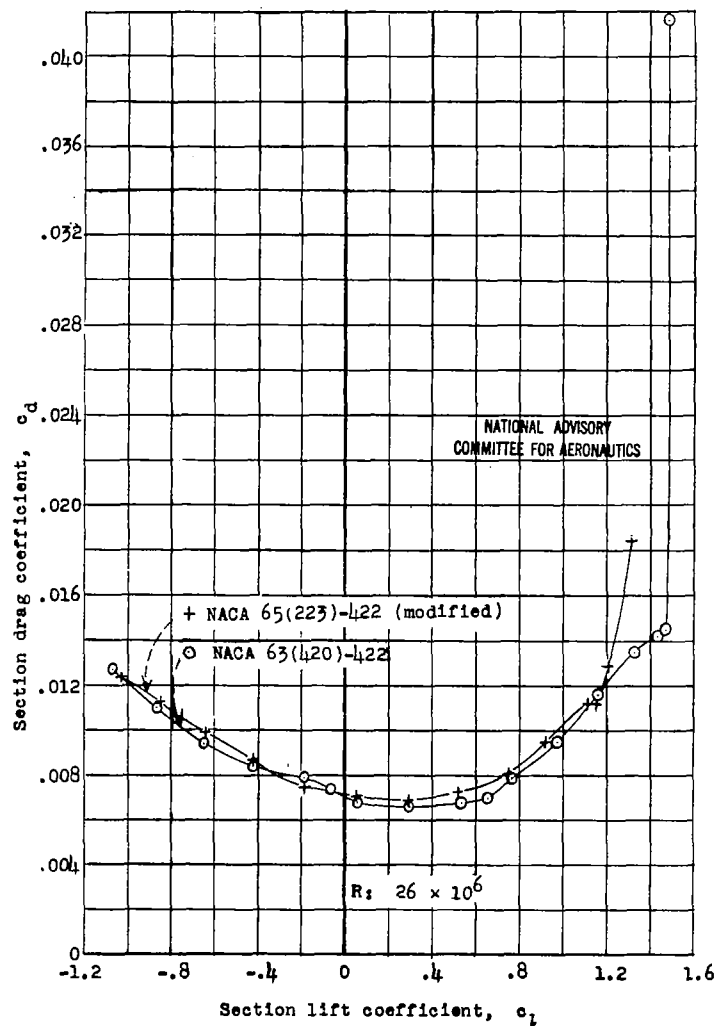


Figure 12.- Drag characteristics of two low-drag airfoils with 0.011-inch-grain roughness at 0.30c.

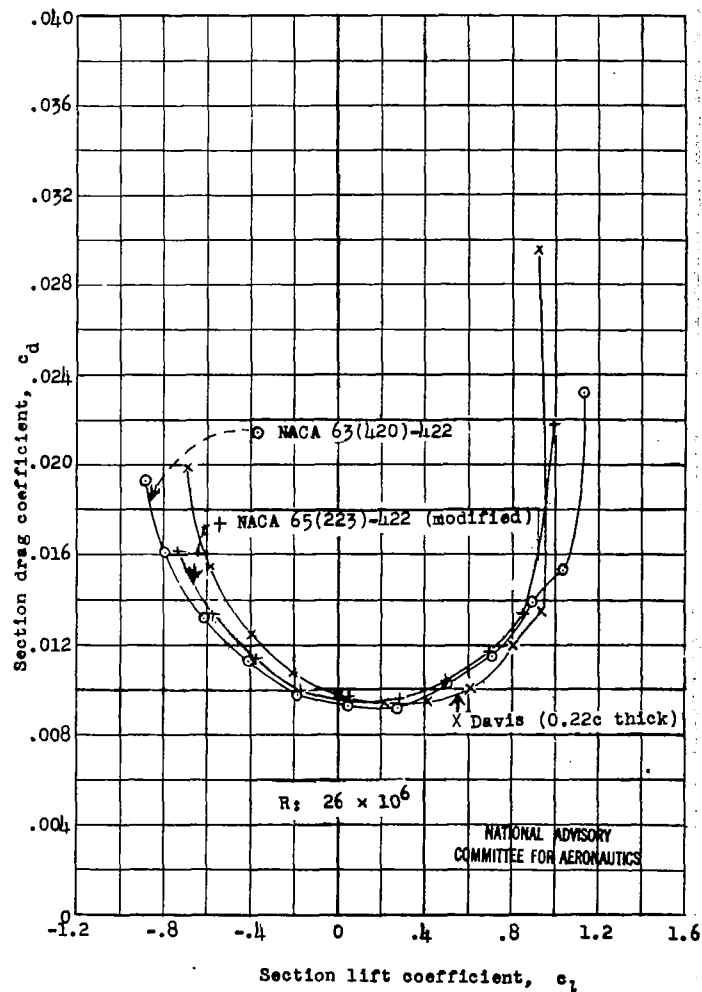


Figure 13.- Drag characteristics of three airfoils with 0.011-inch-grain roughness on the leading edges.

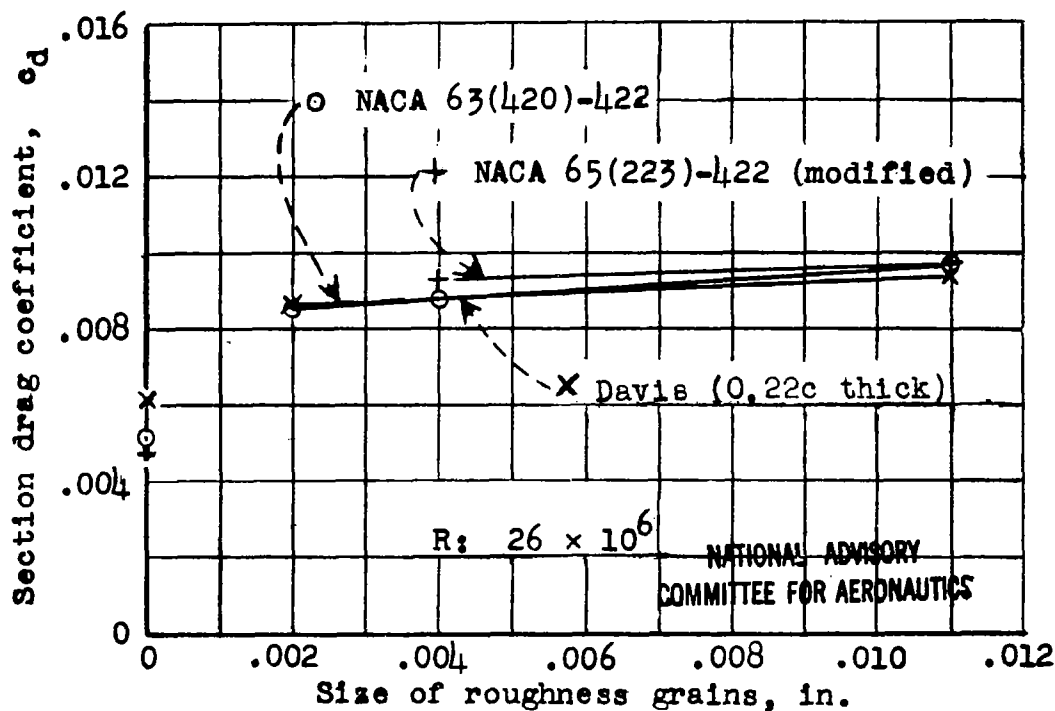


Figure 14.- Effects on c_d at $c_l = 0.4$ of roughness grain size on leading edges of three airfoils.

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